

Enhanced, Passive Cooling for Waterless-Power Production Technologies

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EXECUTIVE SUMMARY

Recent advances in the literature and at SNL indicate the strong potential for passive, specialized surfaces to significantly enhance power production output. Our exploratory computational and experimental research indicates that fractal and swirl surfaces can help enable waterless-power production by increasing the amount of heat transfer and turbulence, when compared with conventional surfaces. Small modular reactors, advanced reactors, and non-nuclear plants (e.g., solar and coal) are ideally suited for sCO₂ coolant loops [Rochau, 2014; Rodriguez and Ames, 2015]. The sCO₂ loop converts the thermal heat into electricity, while the specialized surfaces passively and securely reject the waste process heat in an environmentally-benign manner. The resultant, integrated energy systems are highly suitable for small grids, rural areas, and arid regions.

INTRODUCTION

Under the increasing strain of diminishing energy and water resources, it is crucial that advanced technologies be developed that satisfy the needs of a growing population, while reducing environmental impact. For example, current water cycles require 650 to 850 gallons of water per MWh of generated electricity [Bonano et al., 2016; Musgrove, Rimpel, and Wilkes, 2016]. Clearly, this is unsustainable for a growing population. At Sandia National Laboratories (SNL), our energy and water goals are to reduce the water-consumption footprint required for power production, increase the thermal efficiency of power-production components, and enhance water-condensation techniques. To that effect, we are currently advancing waterless power production for nuclear and non-nuclear technologies, such as miniature and small modular reactors [Rodriguez et al, 2015A; Rodriguez and Ames, 2015], sCO₂ loops [Rochau, 2014], and specialized heat transfer and turbulence surfaces, including fractal fins and swirl [Rodriguez, S. et al, 2015B; Rodriguez and Armijo, 2016; Rodriguez et al, 2016]. The application-rich space for miniature and small reactors is quite diverse, as shown in Figure 1. Therefore, SNL's research for advanced power production systems employs leading-edge computational fluid dynamics (CFD), experimentation, and design.

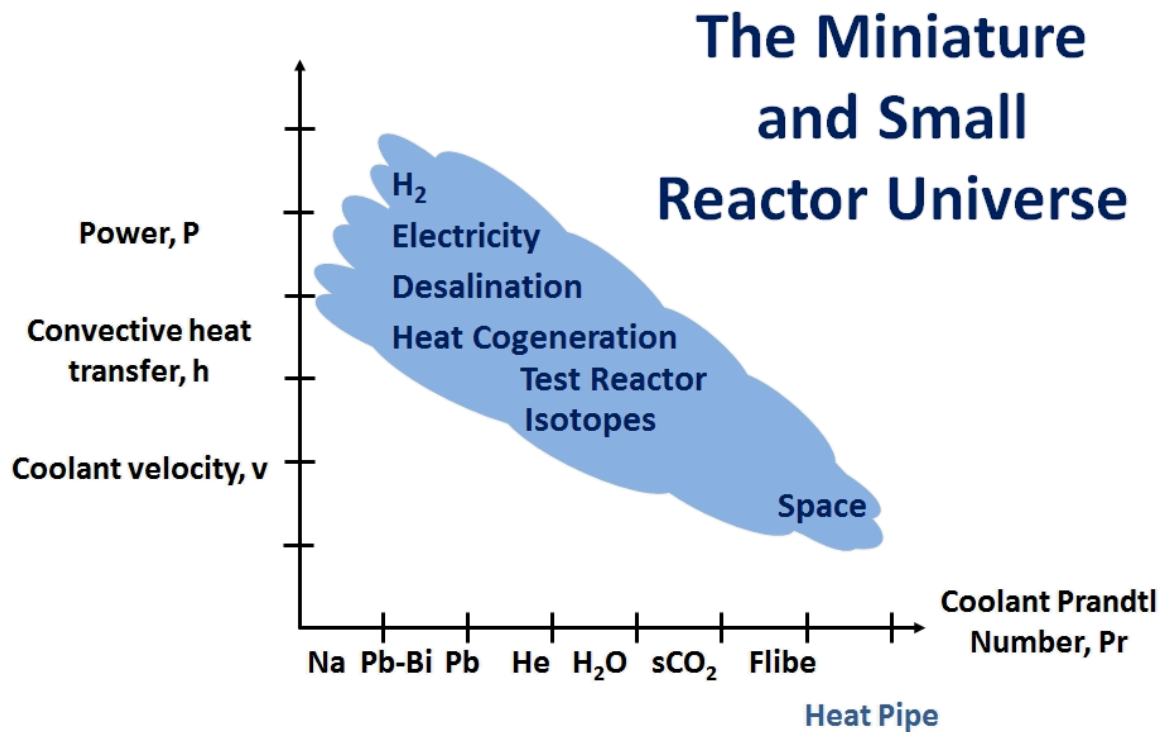


Figure 1. The Miniature and Small Reactor Universe.

FRACTAL SURFACES

Recent advances in the literature show significant engineering gains based on fractal geometries for increased radiative and convective thermal-fin efficiency [Dannelley and Baker, 2012; Dannelley and Baker, 2013]. Fractal surfaces have also been used recently to increase turbulence in regions where mixing was limited [Bukhari, 2014]. Our preliminary CFD and experimental research in fractal fins shows an increase of 30% over conventional fins in the area of solar heat collection, and higher efficiencies are expected as we continue to improve our designs. For example, Figure 2 shows the CFD results of water tanks that are heated externally by the sun. The left hand shows the temperature distribution for a tank using conventional flat fins, while the right hand side shows flat fins with Koch fractals [Rodriguez et al, 2016].

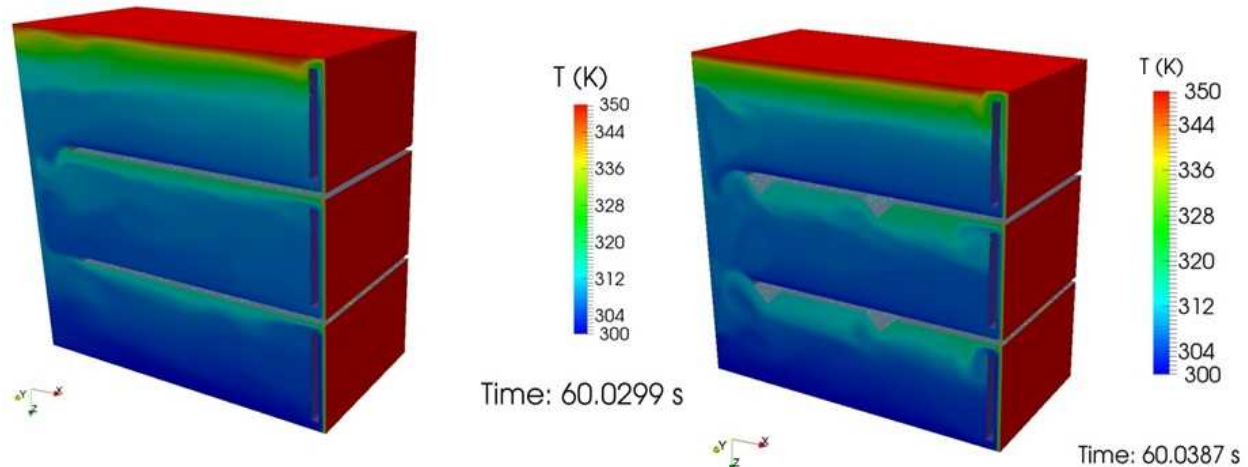


Figure 2. Heat transfer improvement using fins with Sierpinski fractals.

SWIRL SURFACES

The ability of swirl surfaces to selectively modify a flow field to produce more desirable heat transfer and fluid dynamics is the subject of much research in the energy industry [Rodriguez, 2011; Rodriguez and El-Genk, 2011]. For example, we have recently shown that toroidal surfaces increase water condensation by 50% more vs. conventional surfaces [Rodriguez and Armijo, 2016]. Our CFD calculations and experiments demonstrate the ability of toroidal surfaces to selectively separate hotter fluid from natural circulation streams, thereby significantly increasing water condensation and heat transfer. Figure 3 shows our simulation with velocity stream lines as they swirl and move in an upwardly direction, thereby pushing hotter air away from condensing surfaces. The toroidal geometry *therefore isolates the hotter air into a narrow region, thereby allowing the colder air to generate more condensation in the central regions of the system, as shown in Figure 4. This demonstrates our ability to selectively transfer heat and fluids using passive mechanisms for more efficient energy systems.*

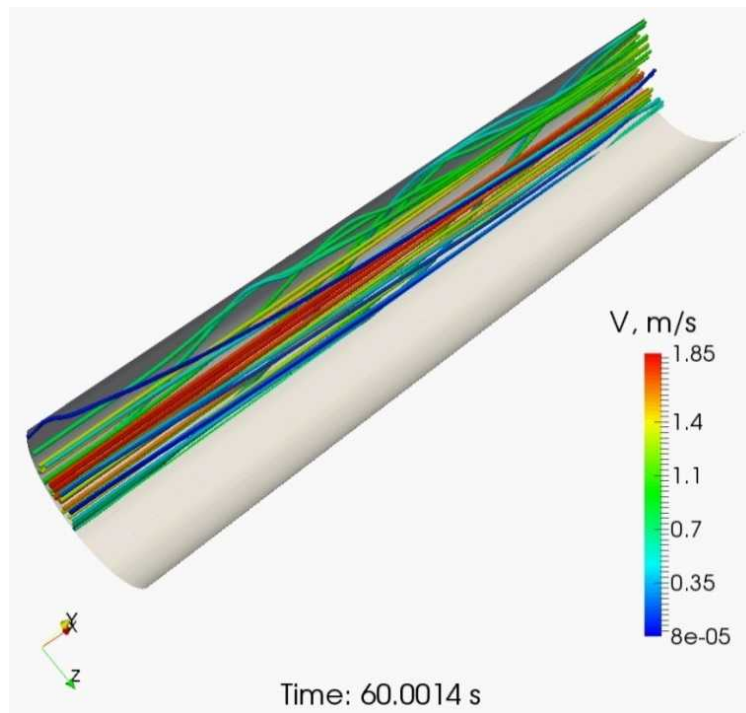


Figure 3. Formation of swirl pattern in a toroidal region.

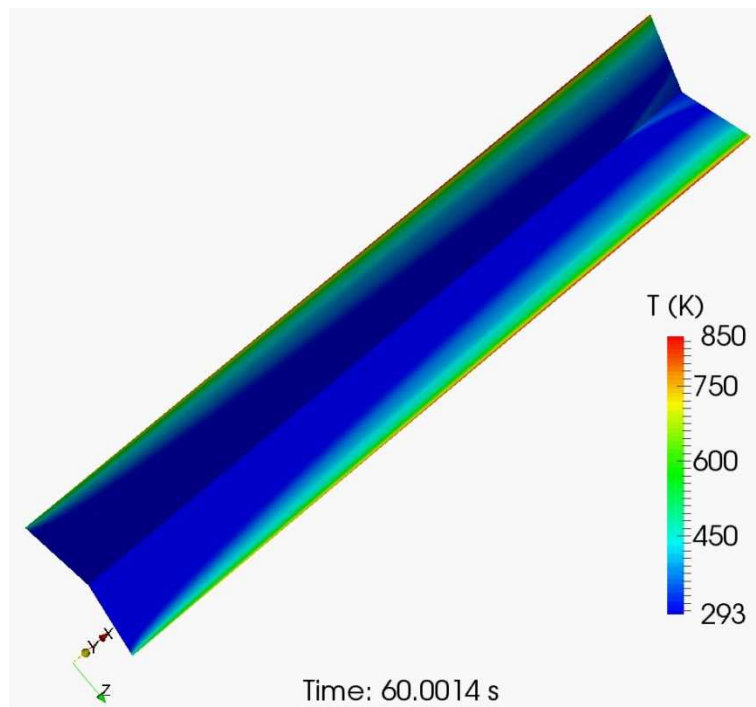


Figure 4. Temperature redistribution using swirl.

In addition, our CFD calculations show that helicoid swirl surfaces produce more fluid entrainment, and therefore increased mixing, heat transfer, and condensation [Rodriguez, S. et al, 2015]. We note that swirling-fluid regions near helical blades recirculate air for additional exposure to the condensation surface, as shown in Figure 5. Swirl also increases boundary layer thickness, and therefore the amount of fluid volume that transfers heat as the fluid passes through the vanes. Because swirl induces a larger pressure drop, it also increases fluid residence time, thereby enhancing the mixing mechanisms due to higher degrees of turbulence. The ability of static swirl vanes to increase heat transfer and condensation was demonstrated with an experiment that included various swirl surfaces, as shown in Figure 6.

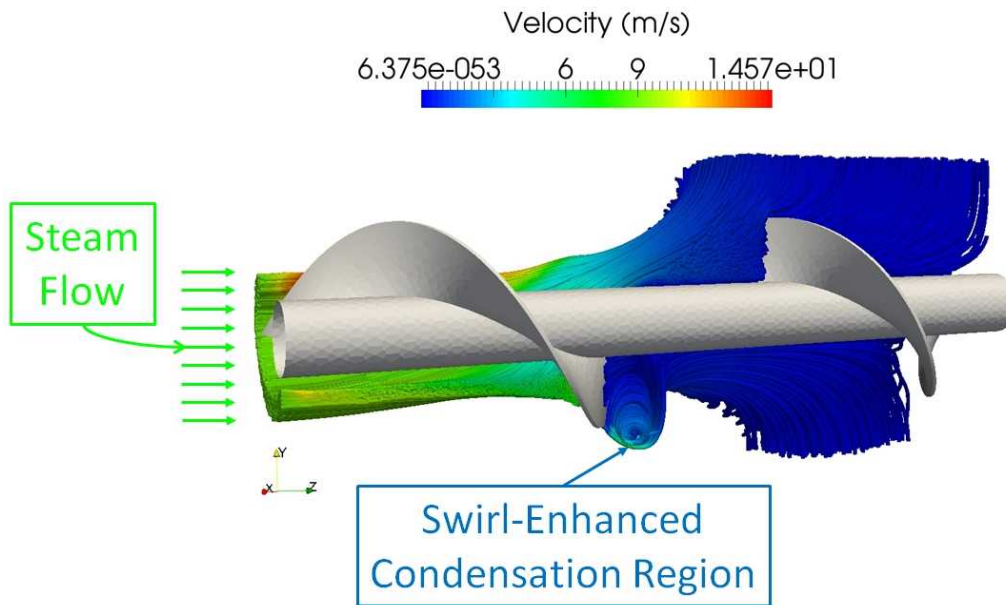


Figure 5. CFD calculation showing the velocity distribution of the swirl vanes.

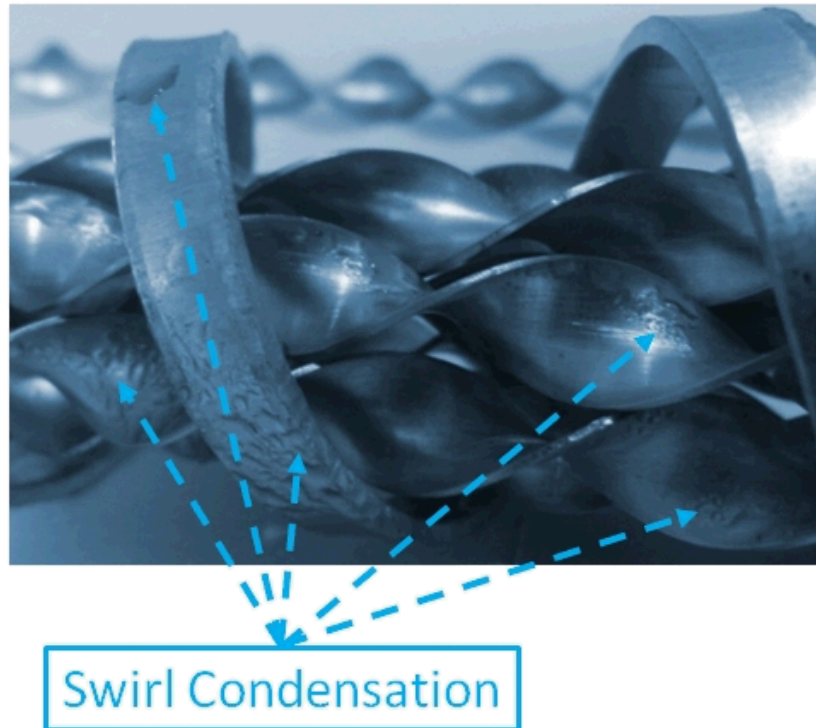


Figure 6. Water condensation on a prototypical swirl device.

CONCLUSION

Energy systems based on passive, advanced heat transfer and turbulence surfaces are important for preserving the water-energy nexus. In particular, smaller quantities of water are required to produce power if conventional heat-rejection surfaces are replaced with fractal and swirl surfaces. Our exploratory research confirms this is the case because the surfaces have higher heat convection and radiation transfer per unit area, as well as higher levels of turbulence. These surfaces are therefore ideal for enabling waterless power production systems, while passively and securely rejecting the waste process heat in an environmentally-benign manner.

REFERENCES

- Bonano, E. et al., “Waterless Power Production”, Sandia National Laboratories, 2016.
- Bukhari M. et al, “An Effect of Fractal Baffles and Impellers with Double Stage 4-Blade Rushton Turbine to Fluid Flow Behaviour in Stirred Tank”, *Applied Mechanics and Materials*, Vol. 660, p. 816-822, 2014.
- Dannelley D. and J. Baker, “Natural Convection Fin Performance Using Fractal-Like Geometries”, *J. of Thermophysics and Heat Transfer*, Vol. 26, No. 4, 2012.

- Dannelley D. and J. Baker, "Radiant Fin Performance Using Fractal-Like Geometries", *J. of Heat Transfer*, Vol. 135, 2013.
- Musgrove, G., A. Rimpel, and J. Wilkes, "Tutorial: Fundamentals of Supercritical CO₂", SRI, 2016.
- Rochau, G., "Closed Brayton Cycle Thermal Capacitor", Sandia National Laboratories, 2014.
- Rodriguez, S., "Swirling Jets for the Mitigation of Hot Spots and Thermal Stratification in the VHTR Lower Plenum", PhD diss., University of New Mexico, May 2011.
- Rodriguez, S. and D. Ames, "Design Optimization for Miniature Nuclear Reactors", American Nuclear Society Winter Meeting, Washington DC, 2015.
- Rodriguez, S. and K. Armijo, "Brazo Strong Condensation System Analysis and Design for Orchard Irrigation Applications", Sandia National Laboratories, 2016.
- Rodriguez, S. and M. El-Genk, "Recent Advances in Modeling Axisymmetric Swirl and Applications for the Enhancement of Heat Transfer and Flow Mixing", *Two Phase Flow, Phase Change and Numerical Modeling*, ISBN: 978-953-307-584-6, 2011.
- Rodriguez et al, "NuScale Spent Fuel Pool Model", Sandia National Laboratories, 2015A.
- Rodriguez, S. et al, "Enhanced Cold-Agriculture Applications for Arid Areas in NM", Sandia National Laboratories, 2015B.
- Rodriguez, S. et al, "Using Fractal Surfaces to Enhance Convective Heat Transfer", Sandia National Laboratories, 2016.